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Magnetically Controlled Optical Plasma Waveguide for Electron Acceleration

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Abstract. In order to produce multi-Gev electrons from Laser Wakefield Accelerators, we present a technique to guide high power laser beams through underdense plasma. Experimental results from the Jupiter Laser Facility at the Lawrence Livermore National Laboratory that show density channels with minimum plasma densities below 5x10^{17} cm^{-3} are presented. These results are obtained using an external magnetic field (<5 T) to limit the radial heat flux from a pre-forming laser beam. The resulting increased plasma pressure gradient produces a parabolic density gradient which is tunable by changing the external magnetic field strength. These results are compared with 1-D hydrodynamic simulations, while quasi-static kinetic simulations show that for these channel conditions 90% of the energy in a 150 TW short pulse beam is guided over 5 cm and predict electron energy gains of 3 GeV.

Keywords: Channel, Waveguide, Optical, Magnetic
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INTRODUCTION

The subject of transporting light from one location to another is of tremendous practical importance. Thanks to the principle of total internal reflection, fiber optics have been used extensively in research and industry to guide light. However, such guiding structures can also be created in plasmas where the damage threshold is significantly higher than in fibers. This makes these structures desirable in research for such topics as high harmonic generation, Raman amplification, and Laser Wakefield Acceleration.

Laser Wakefield Acceleration (LWFA) is a technique which employs a high-intensity laser pulse to drive large-amplitude plasma waves (the wake) in underdense plasma[1]. Electrons become trapped by the wake and gain energy from it over an acceleration length (the "dephasing length") equal to the distance they travel with the wake. In order to reach electron beam energies >10 GeV an optical plasma waveguide is required to maintain the high laser intensity well beyond the inherent Rayleigh length of the system.

Recently a 1 GeV monoenergetic electron beam was demonstrated using a capillary waveguide to maintain the intensity of a short-pulse laser over ∼1 cm [2]. While this approach to guiding has certain advantages, such as pre-ionizing the gas fill electrically and high repetition rate, there are also distinct limitations. The size of the waveguide is fixed by the capillary construction, eliminating shot-to-shot tuning capabilities, while impaired guiding and/or misalignment can damage the capillary. The acceleration lengths in previous studies were further limited to a few millimeters [3, 4, 5] by the use of gas jets. We propose a scheme for producing an optical plasma waveguide that is well suited for multi-GeV LWFA, promising to extend acceleration lengths to several centimeters.

To produce this waveguide a laser pulse is fired into a gas target in the presence of a coaxial magnetic field. When an external magnetic field is applied parallel to a laser in a plasma, thermal transport transverse to the beam is inhibited [6]. This drives high electron temperatures along the laser axis, resulting in a pressure gradient which expels electrons away from the center of the laser. The choice of applied field strength determines the radial electron density profile in the plasma [7], which allows for the tuning of an optimal waveguide structure for LWFA.

This paper presents an approach for guiding a laser over many centimeters that employs an external magnetic field to produce an optical waveguide. In order to achieve long waveguides, axially uniform magnetic fields are necessary. We have developed a 20 cm long solenoid capable of delivering uniform fields over 12 cm. This allows for guiding over much greater distances than have previously been demonstrated, enabling longer acceleration lengths and greater energy gains for LWFA systems.

HARDWARE DEVELOPMENT

We have previously demonstrated the ability to produce plasma channels in mm-scale gas jets using the Jupiter Laser Facility at the Lawrence Livermore National Laboratory [8]. In order to extend this capability to the multi-cm length scale, each sub-system needed to be modified for longer scale lengths. This involved the development of both a new magnetic field coil and gas delivery system.

While our previous solenoid was able to deliver peak magnetic fields above 25 T, the spatial uniformity was limited to few-mm scales by the construction techniques [9]. In order to increase the length of the uniform field region, the solenoid shown in Fig. (1) was developed. The details of the design are included in Reference [10], and it is evident in Fig. (1c) that the field is uniform over 12 cm. The increased length of the coil has come at the expense of peak field which is shown in Fig. (2) to be limited to 4 T at a peak current of 90 kA.

The final step to achieving a multi-cm long system is to improve the gas delivery system. This is achieved by replacing the gas jet with a 20 cm long gas tube. The 2 cm diameter tube is inserted coaxially inside the solenoid, and He gas is injected to fill pressures up to $4\text{x}10^{18}$ cm^{-3} neutral density. The neutral gas density profile has been measured along the length of the tube, and is shown in Fig. (3) to be uniform throughout the measured region.

EXPERIMENTAL SET-UP

Preliminary experiments using the 20 cm-long solenoid to produce long plasma channels have been performed at the Jupiter Laser Facility, Lawrence Livermore National Laboratory (LLNL) [6]. The plasma is formed by a long (1ns), 1ω (1054 nm) laser pulse which is focused through either an f/25 or an f/50 optical system to the center of the solenoid at intensities up to 10^{15} W/cm^2. The spot size of this beam has been measured at f/50

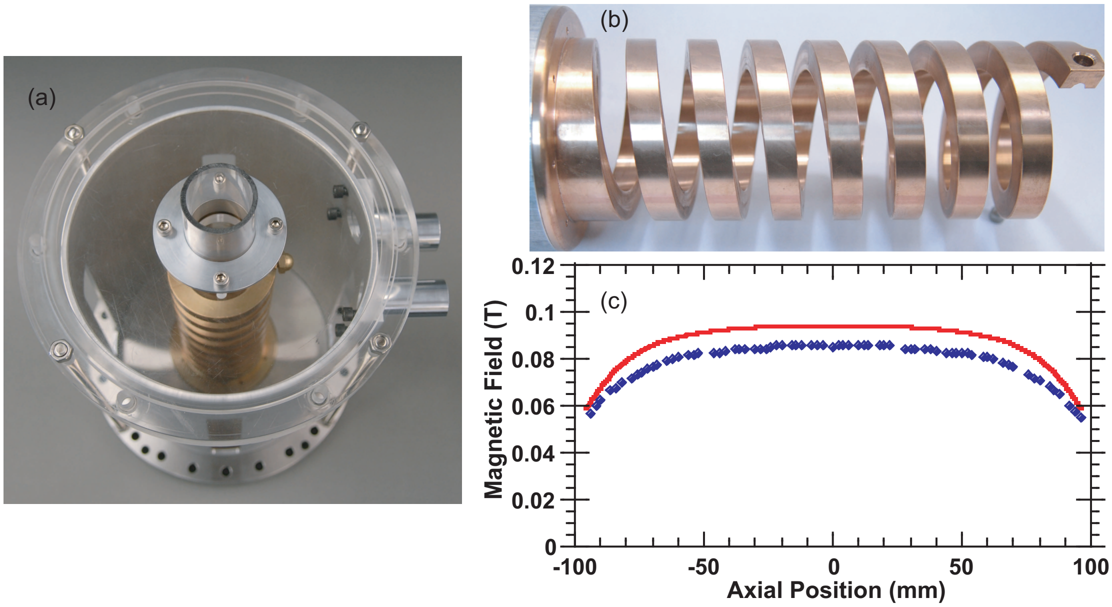

FIGURE 1. (a) The solenoid is bolted to a stainless steel flange, while an aluminum shell returns the current to high voltage coaxial cables. (b) The 20 cm-long solenoid was machined out of a solid block of phosphorus bronze. (c) The measured axial magnetic field profile of the solenoid (blue) agrees well with the profile calculated in [10] (red). The measurement demonstrates that the field is uniform over 12 cm.

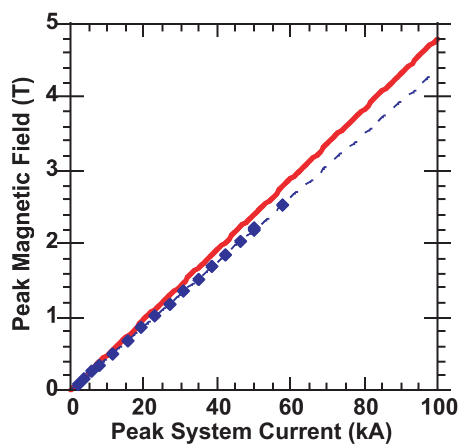

FIGURE 2. The peak magnetic field is measured at the center of the solenoid using a pick-up probe(blue). Linear regression of the data indicates that the field scales with the peak system current at 44 mT/kA. The data are compared to [10] (red), and agree to within 10%.

and is shown in Fig. (4) to be less than 100 μm radius over 6 cm. Fig. (4a) shows that this system is capable of producing $\sim$5 cm long plasma columns. The image is recorded by a gated charge-coupled device (CCD) camera that time averages the visible plasma emission for 20 ns over the length of the solenoid.

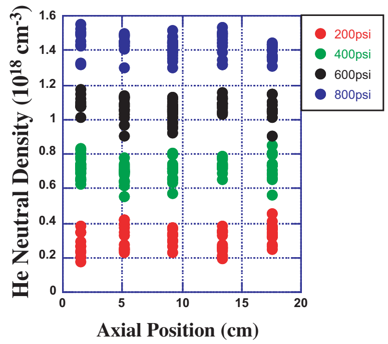

FIGURE 3. The neutral He gas density is measured along the length of the 20 cm gas tube for a range of backing pressures. The density is uniform over the length of the tube, and scales linearly with applied backing pressure.

This experiment has also been performed with the same laser system in an f/25 focusing arrangement with spatially resolved interferometric plasma density measurements. The interferometry beam contains $\sim$10 mJ of 1ω light in a 200 ps long pulse arriving at the plasma $\sim$2 ns after the rising edge of the heater beam. Light is collected by a 2 inch diameter, 50 cm focal length lens and relayed onto a 1024x1536, 12-bit CCD camera; the system magnification is 2.3. In this configuration, long plasma channels are shown to be produced with 25 J of incident laser energy and a magnetic field of 3 T in a static He gas fill of 2.5x10^{18} cm^{-3} neutral density. The image shown in Figure 5a is a composite of 5 successive shots where the location of the interferometer is held fixed while the heater beam best focus is translated along the axis of the solenoid. Figure 5b shows the Abel inverted density profile along the plasma channel at the positions indicated by the arrows. It is clear from the inversions that a density channel is formed for more than 2 centimeters along the axis of the heater beam. Also, note that the fringe pattern continues off the left edge of the image, so that 2 centimeters is a minimum estimate for the length of the channel.

For the same 25 J of laser energy, but with only half of the initial He neutral density, Fig. (6) shows the dependence of the channel parameters on the applied magnetic field strength. In the case of no applied field, the density is peaked on axis and smoothly decreasing radially away from the center of the plasma. When a 3 T field is applied, a clear channel is formed. The minimum density is below 1x10^{18} cm^{-3}, with a full-width at half-maximum density of 50 μm. The dynamics of the channel formation are the result of the quenching of non-local heat transport effects. The magnetic field inhibits the transverse motion of electrons, insulating the center of the plasma against energy loss to the surrounding cold region [6]. This drives a high electron temperature along the laser axis, and the resulting thermal pressure gradient expels electrons outward. At the maximum applied field of 4 T, no channel is formed. Thus we are able to form and control the shape of our plasma channels by changing the strength of the applied magnetic field.

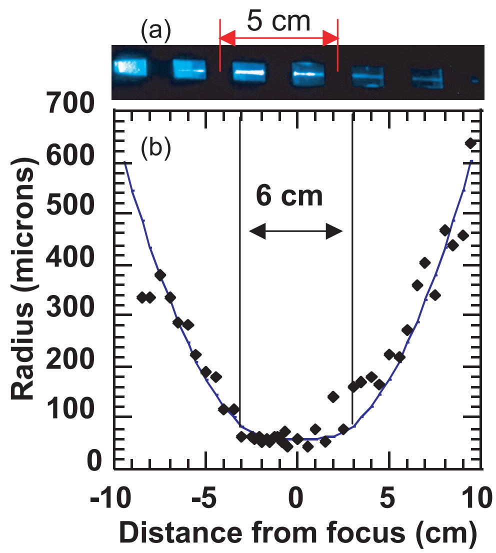

FIGURE 4. (a) Plasma columns in excess of 5 cm are produced when a 100 J laser is fired into a 1.5×10^{18} cm^{-3} neutral density He gas fill. Visible plasma emission (400 nm $< \lambda <$ 800 nm) is collected by a CCD camera. The spaces between the turns of the solenoid are 1.3 cm wide. (b) The spot size of the heating beam has been measured to be less than 100 μm radius over 6 cm in the propagation direction of our f/50 optical system.

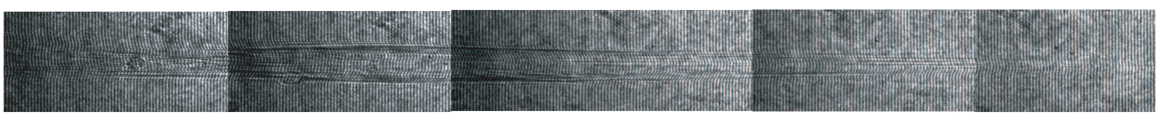

FIGURE 5. The interferometry field of view is 6 mm in the axial direction. Holding the position of the interferometer fixed, the heater beam focusing lens is translated in 5 mm increments on 5 successive shots, enabling us to measure the plasma density over a length of $\sim$2.5 cm. This composite image demonstrates that a channel is formed over this entire length when a magnetic field of 3 T is applied, as is shown by the Abel inverted density profiles taken at the positions indicated by the red arrows. Note that the fringe shifts continue further from the left edge of the image, so that 2.5 cm is only a minimum estimate of the channel length.

SIMULATION RESULTS

MHD simulations in 1-D qualitatively reproduce the measured effect of the external magnetic field on plasma channel formation [8]. However, the field required to inhibit channel formation is much higher in those simulations than is observed here. The hydrodynamics code HYDRA has been used to perform 3-D simulations of the channel described above[8], with results indicating that the channel should be stable over >5 centimeters. Using these parameters as input conditions, we have used the quasi-static kinetic code WAKE to simulate the propagation of a short-pulse laser inside the channel. Our simulations show that 90% of the energy in a 150 TW short pulse beam can be guided over 5 cm in these channels and predict electron energy gains of 3 GeV [8]. This is in good agreement with analytic calculations which indicate that for plasma densities

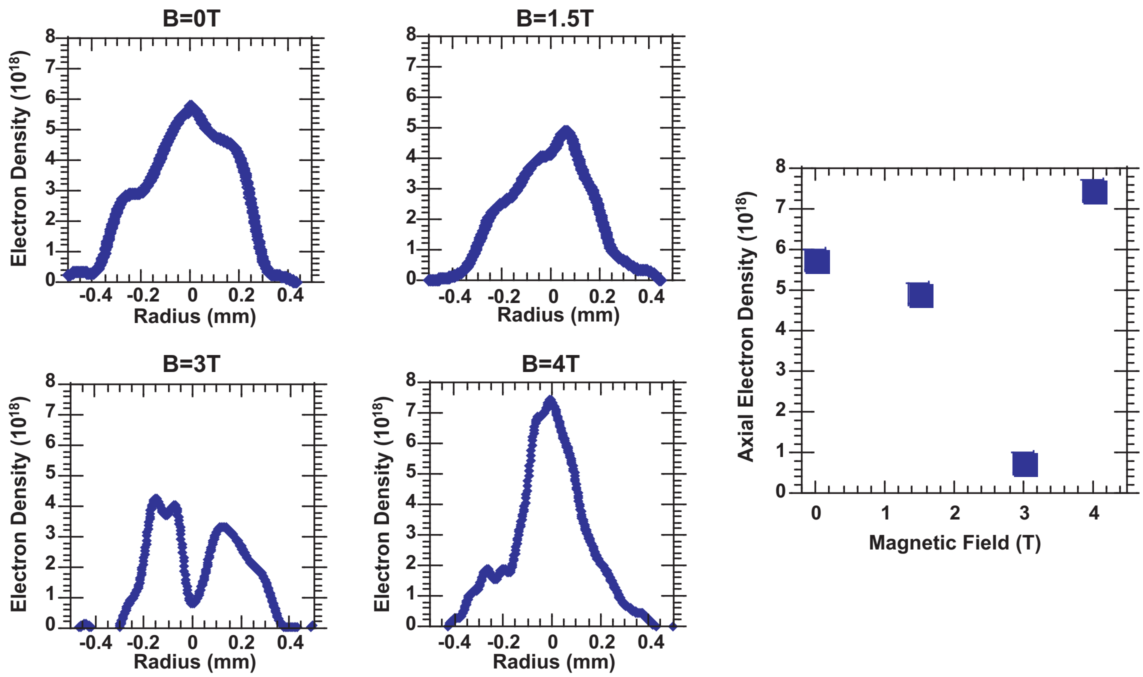

FIGURE 6. At one location in the plasma, the radial electron density profile has been measured as a function of the applied magnetic field strength. In the absence of the field, the profile is peaked on-axis and falls off smoothly with increasing radius. When a 3 T field is applied, a channel with minimum density below 1×10^{18} cm^{-3} is formed. Increasing the magnetic field to 4 T is sufficient to suppress channel formation by confining electrons in the vicinity of the heater beam.

of 10^{18} cm^{-3} (corresponding to 5 cm dephasing lengths), a 200 TW system will produce a multi-GeV electron beam [11].

CONCLUSION

We have presented a platform for guiding a high-power, short-pulse laser beam for more than 5 cm using a magnetic field and a laser to form an optical plasma waveguide. By applying a uniform magnetic field parallel to the laser during plasma formation, transverse electron thermal transport is inhibited, allowing control over the radial electron density profile. The laser beam intensity has been measured to be nearly uniform over 6 cm, while the magnetic field is uniform over twice that length. These parameters have been chosen to be consistent with requirements to produce monoenergetic GeV electron beams from LWFA.

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